RESEARCH ISSUES IN AD HOC NETWORK DESIGN

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ABSTRACT

This paper explores and develops some of the critical research issues in ad hoc network design. Although ad hoc network technology is critical to such major Army Programs as FCS and WIN–T, the design of ad hoc networks to meet a set of military technical and operational requirements has been shown to be more of an art than a science. For purposes of this paper, an ad hoc network is only the communication subsystem of a C4ISR network. The problem domain is exceedingly complex and rich with numerous tradeoffs, but is hampered by a lack of mathematical descriptions, tools and relationships to conduct those tradeoffs and analyses. In contrast to wired networks, where only the traffic loading is stochastic, wireless networks themselves, in addition to the traffic loadings, are also stochastic in nature. This dual stochastic nature of both the traffic and the network carrying the traffic poses significant challenges in both the modeling and design of mobile ad hoc networks. In this paper we consider network design at three distinct but interrelated levels. At the highest level, we are concerned with the overall network structure, specifically network connectivity, network capacity (in terms of end–to–end throughput/goodput, delay, and probability of packet loss) and network survivability. We present and discuss some mathematically based definitions of these quantities. At the next lower level, we discuss some issues with the network node design. At this level, we are concerned with issues of link design, media access, transmitter power, etc. Finally, at the lowest level of design, we present some issues in the evolving area of cross layer protocol design. Finally this paper concludes with discussion of some research issues in the design process.

1. BACKGROUND ON AD HOC NETWORKS

The term “network” needs some clarification. In some circles, the term “network” refers to both the packet communication subsystems as well as the user subscriber end device. This may be more properly called a C4ISR network. For the remainder of this paper, we shall us the term “network” to be only the communications subsystem or packet network. In addition, unless otherwise stated, the term “network” means “mobile ad hoc network”. In terms of the ISO–OSI reference model, this means the network layer and below, down to the physical layer.

As previously noted, the Army is rapidly developing a new communication network capability based in part on the ad hoc networking model. In contrast to the familiar digital cellular networks that are common place today, ad hoc networks assume no fixed infrastructure or cell towers. While cell towers provide an advantage for the propagation of RF energy, the typical ad hoc network has no such capability. In addition, stationary cell towers are located to optimize RF coverage, typically after detailed site survey and mathematical modeling, to the individual mobile subscriber nodes. To provide an equivalent capability to the ad hoc networks, aerial relays, typically on UAV’s may be employed in support of an ad hoc network.. While UAV provide some of the advantage of a cell tower, the fact that they are not stationary, and must return periodically for refueling adds some additional complexity to the ad hoc network not present in the cellular environment.

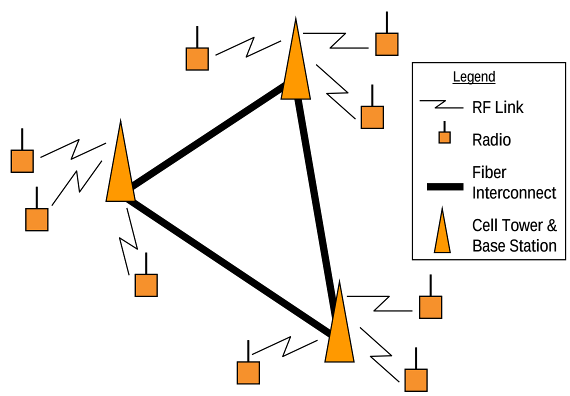

Figure 1. A digital cellular network

Digital cellular technology also has the advantage that each of the mobile subscriber nodes (cell phones) typically communicates with only one cell tower at a time. Therefore the routing problem is minimized (always up to the cell tower or down from the cell tower to the cell phone). Furthermore, to provide additional coverage, the cell towers themselves are inter–connected redundantly with high speed, reliable fiber optic communication links (Figure 1). Typically, Army networks rely only on RF communication, with the resultant well known bandwidth and reliability issues.

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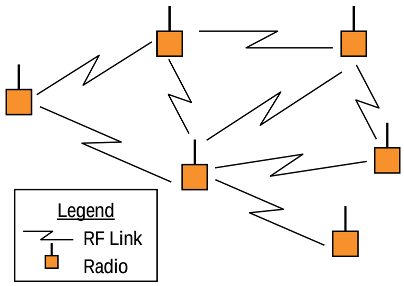

Figure 2. A mobile ad hoc network

Another advantage of the digital cellular architecture is that the communication and network processing can be asymmetric, with most of the heavy computation performed in the stationary base station located in the cell tower, and only the minimal computation performed in the subscriber's mobile handset.

Another capability that distinguishes the ad hoc network is that typically every node is essentially the same as every other node, and that any node can be a relay for traffic of any other node. This is essential to provide the necessary RF coverage, as well as to provide potentially redundant paths for enhanced data transmission reliability.

A final attribute of ad hoc networks is that any or most of the nodes can be in motion at any point in time (Figure 2). Obviously this is not the case with the digital cellular technology with its fixed infrastructure of cell towers.

One may ask, why is the Army focused on ad hoc network technology when digital cellular technology offers so many potential advantages? The answer is simple; a system that requires a fixed infrastructure of 100+ foot cell towers is inappropriate for the highly mobile, tactical Army battlefield environment.

2. NETWORK ANALYSIS VS. NETWORK DESIGN

It is important to distinguish between the design problem and the analysis problem. In the analysis problem, we are provided with a solution to a problem that is claimed to have a certain level of performance or functionality. It is therefore the analyst's task to show that the claims are either true or false. Typically, this is done through a combination of simulation, emulation, analytic modeling or prototyping as discussed later in this paper. With this approach, there is always an issue as to accuracy and fidelity of the simulation and/or model as it relates to the "real" network that will be developed and implemented.

Network design is a synthesis processes. That is, we are provided a set of goals or requirements and asked to create or generate a network solution that meets or exceeds those goals. Thus, the solution that is created for ad hoc networks depends on the creativity and inventiveness of the design engineer. In other types of networks such as the digital cellular and wired Internet, some software tools are currently available to assist the design engineer (B.T. Doshi, et. al, 1995). However, as of this writing, there are no such software tools available for the designer of ad hoc networks.

3. WHAT EXACTLY IS NETWORK DESIGN?

The network design problem usually begins with a goal that a set of users and their associated traffic loading (offered load) that is to be carried by the network. Additional constraints, such as survivability and/or energy usage may also be provided. In conventional digital cellular networks, the problem initially focuses on determining the location and number of base stations needed to provide adequate RF coverage. Once the base stations and cell towers have been located, they are interconnected thru high speed fiber optics, where capacity assignment, flow assignment, and routing are among the problems to be solved (M. Pioro, et. al., 2004)

For mobile ad hoc networks, we decompose the overall network design problem as three problems related in a hierarchical top down fashion. At the highest level we are concerned with overall network wide problems and issues. These include the goals of end–to–end throughput/goodput, delay and data reliability as seem by the user or subscriber. In addition, we are also concerned with support for user node mobility and reliable connectivity to the network as a whole.

As many of the overall network characteristics are determined in part by the individual nodes (or radios) themselves, the next logical component of network design is the nodal or node design. At this level of design, we are concerned with the overall characteristics of the node that contribute to overall network behavior. This includes nominal transmission power and receiver design (which obviously impact the one hop communication within the network), but may also include issues such as link initialization and recovery due to node motion or jamming.

Finally, the lowest level of network design consists of protocol design for the network, data link and physical layers. As well known, communication protocols implemented largely in software govern the flow of user information through the network by a collection of algorithms and control information exchanges. Protocols have been studied and designed for many years, and volumes have been written about them. To date, most protocols are and have been designed in an "ad hoc" fashion, more like trial and error as contrast with a more structured and orderly approach that is typical of the network and nodal design as mentioned above.

Each of the design components will now be described in some detail.

3.1 Design at the Network Level

As previously mentioned, network level design is concerned with providing capabilities that are most associated with meeting or exceeding the end to end user requirements. Most often, they are stated in terms of IER (Information Exchange Requirements) and for a particular scenario or scenarios. From a networking point of view, these are essentially end–to–end requirements. However, there are also a number of implicit requirements, the most dominant one being the connectivity or RF network coverage problem as indicated below.

3.1.1 Connectivity RF Coverage Problem

One way to view the RF coverage problem is the determine probability that a given user will have access to the network. This implies that a given user will be within range of one or more other radio nodes over a wide range of conditions. In order to address this, the concept of node density may be used, as it relates to the average number of nodes per unit area. However, there may be situations where the node density is too low, or a given node may become isolated. In this situation, either additional relay nodes, either ground based or in UAV's may be required. Finally, due to node location, node clusters may result.

Several metrics have been developed to quantify connectivity. The one that is most useful is given by:

$$\text{Connectivity(N)} = \frac{\sum_{i=1}^{k} n_i(n_i - 1)}{N(N-1)}$$

where

N is the total number of nodes
K is the number of isolated clusters
n_1 is the number of nodes in an isolated cluster.

3.1.2 Capacity/Delay problem

The capacity/delay problem is associated with providing the end users their desired rate of data transfer as throughput or "goodput" at their desired end–to–end delay. Throughput is the rate of data including possibly duplicated data that is received at a destination or group of destinations. Goodput, on the other hand, is the rate at which unique or non replicated data is received at the receiver or group of receivers. We note that throughput/goodput is measured in terms of bits/second or packets per second over a large number of received bits or packets. On the other hand, the delay is the time difference between the transmission of a packet and its reception, as averaged over many packets as well. Therefore throughput and delay are different but related quantities. We also note that the throughput achieved may be independent of the number of intermediate points through which it was relayed, but the delay seen at the end user is highly dependent on the number of intermediate relays that packet was sent though.

The capacity and delay problem has been formulated mathematically as a linear programming (LP) problem. In this formulation, the data is modeled as a flow, or stream, rather than individual packets. Using the flow based approach, each of the links in the network has some maximum capacity in packets per second. In one formulation of capacity as a LP problem, we try to maximize end–to–end flow, subject to the constraint that the flow on each link must be less than the maximum capacity of that link. An additional constraint is that at intermediate relay nodes, flow in is the same as flow out, i.e. flow is conserved.

While this formulation is quite useful for wired and point–to–point networks, it is only a starting point to mobile ad hoc networks. The flow based model only addresses either the average or the peak requirements, and not the dynamics of individual packets in transient effects. In highly mobile ad hoc networks, the transient effects may dominate overall network performance. In addition, the mutual interference between nodes is not represented due to the point–to–point graph theoretic model.

3.1.3 Survivability Problem

The survivability problem focuses on the goal that mobile ad hoc networks for use in the Army's tactical environment must retain function and performance in spite of the loss of nodes due to battle damage or loss of link capacity due to enemy jamming. A number of graph theoretic algorithms are available to predict the effect of node or link loss. In addition, a number of other algorithms exist that can be employed to provide some excess capacity so that the loss of some nodes or links would not cause an undue loss of network performance.

3.1.4 Energy Efficient operation problem

As many tactical networks are battery powered, the optimum use of available energy is another critical design issue. A fairly large body of work is available that addresses energy utilization in mobile ad hoc networks. There are several approaches to the problem including but not limited to the global energy usage as averaged over all nodes or that for a particular subset of heavily utilized nodes. Generally speaking, it is more useful to globally optimize energy usage in that it typically results in a lower probability of a network become fragmented due to nodes that fail due to loss of battery power.

3.1.5 General Problem Formulation at the Network Level

In general, a number of network level designs have been posed successfully as linear or non–linear programming problems. In the case of linear programming approach, an optimal solution is guaranteed, while non–linear constraints or non–linear objective functions don't guarantee optimal solutions.

3.2 Design at the nodal level

Design at the nodal or radio level can deal with a wide range of design decisions. Here, however, we are concerned with only those decisions and tradeoffs that affect the nodes' network level performance. The major of these decision include the effective RF transmit power, data link design, and effective signaling rate.

We note that there is a fairly tight interplay between the node design and network design. For example, increasing the node's transmit power may provide an increased number of one hop neighbors, as well as increasing the available Shannon capacity in a limit with fixed bandwidth. In addition, due to the uncertainty of the link propagation loss, typically a large number of propagation models (Rayleigh, Rican etc.) should be considered in the data link design. Typically, in ad hoc network environment, we do not know a priori which propagation environment the link is operating in.

Typically, the link performance is provided in AWGN (Additive White Gaussian Noise) environment, which provides a most optimistic result. In reality, we would need to represent the receiver noise figure, as well as a more realistic RF propagation loss. It should be observed that there is a substantial amount of uncertainty that needs to included, specifically, the receiver's noise environment, as well as the propagation loss coefficient and shadowing effects. How this uncertainty should be handled is still an active area of research. Obviously, if the worst case of all uncertain variables is assumed, then in many cases the link may be substantially over designed. The equations below summarize uncertainty two path loss models, the first with uncertain path loss exponent, and the second with a log normal random variable to represent fading.

$$P_r = P_x \left(\frac{d_{ref}}{d}\right)^{\alpha}$$

$$For \quad Shadowing \quad by \quad \log - normal$$

$$P_r = P_x \left(\frac{d_{ref}}{d}\right)^{\alpha} \psi$$

$$f_{\psi}(x) = \frac{10/\log(10)}{\sqrt{2\pi}\sigma x} \exp\left(-\frac{(10 \log_{10} x)^2}{2\sigma^2}\right)$$

$$where$$

$$P_r = received \quad power$$

$$P_x = transmitte\,r \quad power$$

$$d_{ref} = the \quad reference \quad dis\tan ce$$

$$d = \quad the \quad dis\tan ce \quad at \quad which \quad power \quad is \quad received$$

$$\alpha \quad = \quad the \quad propagatio\,n \quad \exp onent$$

$$\psi \quad = \quad \log - normal \quad random \quad \mathrm{var}\, iable$$

$$f(x) = \quad pdf \quad of \quad \psi$$

3. 3 Design at the protocol level

The design at the protocol level deals with the construction or selection of a protocol to provide the required level of performance. This area is perhaps the least understood and least researched from a performance point of view. Typically, protocols are designed with an attempt to meet some functional goal, and not with a specific performance goal in mind. Protocol design is the most creative and inventive of all the design levels for a number of reasons.

First, we know from Turing complexity theory that having a general purpose algorithm that can be used to generate other algorithms is mathematically impossible. All we can hope for are some general rules that can be followed and result in some good designs. Typically, protocols are design in an "ad hoc" fashion, and then extensively simulated to determine performance and to discover design flaws. The simulation approach itself has numerous flaws as indicated in a recent paper (T. Andel and A. Yasinsac, 2006)

The design limitations not withstanding, a fairly large number of protocol functions are required to be implemented, and have a direct impact on the overall network performance. We list the major ones here as:

1) Network Layer Functions
   a) Network Initialization
   b) Node or Node Group entry or exit
   c) Routing (to include path finding, forwarding, connectivity determination, and QOS)
   d) Alternate Routing
   e) Addressing
   f) Dynamic Topology Control
   g) Flow control
   h) Congestion control
   i) End–to–End security

j) Network Access
k) Node mobility support

2) Data Link Functions
a) Channel Access (in shared environment)
b) Link Synchronization
c) Link Establishment / Maintenance
d) Link Flow Control
e) Link error control (FEC, ACK, or both)
f) Data Link reliability in dynamic environment

3) Physical Layer Functions
a) Data modulation/ demodulation
b) Physical Layer Synchronization
c) Frequency Selection

It is clear that a large number of protocol functions are required to support a node in an ad hoc network. But how are they to be designed? As of now, the state of the art is that they are invented without any formal process, but simply created from human creativity. Then after they are designed, they are simulated, prototyped, or emulated to determine their performance. Thus, the concept of "design to performance requirements" is currently beyond the state of the art, and today protocol design is a manual and technically challenging process.

4. GENERIC NETWORK DESIGN METHODS AND TECHNIQUES

There are currently a number of techniques or approaches to ad hoc network design. We will discuss them without any specific order.

4.1 Analytical Methods

In this case we assume that closed form analytic expressions are available to be used in the design process. For example, the well known result from queuing theory expresses the expected delay as a function of applied load on a single communication link. Using the M/M/1 queuing equation as a model for a single link, the average delay is given by:

$$E(T) = 1/(\mu C - \lambda)$$

where

$E(T)$ is the average delay
λ is the average (Poisson) arrival rate
C is the link signaling rate (in bits/second)
$1/\mu$ is the average packet length (assuming exponential packet length distribution)

While the equation above is exact for the conditions specified (i.e. exponential packet length distributions and Poisson packet inter–arrival times), its application as a general design equation is limited by these assumptions. In addition, this points to the major problem in trying to use analytic equations in the design process i.e. the fact they only hold for a limited number of special cases that usually are not typical of the designs to be achieved. Nonetheless, they may be a starting point for many designs. Kleinrock (Kleinrock 1964) and others have extended this basic result to provide the average delay of a network of interconnected queues using the celebrated "Kleinrock -Independence" assumption.

4.2 Event Driven Simulation

In this design option, a detailed event driven simulation is developed and numerous designs are simulated. The basic problem with this is that simulation is really an analysis tool, and the human designer is left on his (her) own to do the design work. None the less, the simulation can provide some quantitative results to describe the performance of the design. A more significant question is the actual use of the simulation. The event driven simulation requires that specific numerical values be used for things like average packet length, and the like as well as pseudo–random seed to be used for all "random" or stochastically generated data. This brings up another weakness in the simulation based design, in that the results are valid only for those specific numerical parameter values, and the numerous simulation executions, with statistically independent seeds are required to generate statistically valid results. For 30 or fewer simulations executions, the Student–t distribution can be used to generate valid mean values while the chi–squared distribution should be used to provide accurate variance calculations. This implies that to get statistically valid results multiple (up to 30) independent runs (with different seeds) are required to get results for a single set of input parameters. While this can be done, the potentially large number of independent simulation runs limits the general applicability as a desire technique.

4.3 Prototyping

Prototyping generally means that a limited version of the target network is designed, developed tested and evaluated. Typically, the most technically challenging components of the network are implemented to fully examine the design issue present. Since the prototype has lesser functionality than the final target network, the engineering costs are less and the prototype network components are easier to analyze, test, and evaluate. This prototyping approach to network design has been successfully used on a number of CERDEC–STCD programs, including most recently the MOSAIC, PILNSER, and SLICE/SRW efforts.

The main difficulty with prototyping is that it is fairly costly in terms of time and dollars, and only limited design options can be explored. In addition, having only a limited prototype usually limits the total number of units that can be built, and hence scalability issues can not readily be explored and investigated.

4.4 Emulation

Emulation usually means that a surrogate capability is designed and built that has the full functionality of the desired end system, but is implemented in a simpler and cheaper package. Emulation may have included scaled versions of the final network capability, where the emulated network nodes may have reduced transmit power and/or data rate. Since only a scaled version of the capabilities of the final target network is implemented, there is always the question on how this affects the final system. It should be noted, however, that where accurate mathematical models are available, problem in things link aircraft wing design and surface ship hull design can rapidly and accurately be explored but this emulation technique. To date however, emulation has found little applicability in ad hoc network design

4.5 Linear (non–linear) Programming (LP)

The linear programming (LP) approach requires that a portion of network design problem be formulated mathematically as a set of constraints, equations, and a function to be optimized. A number of recent papers, and in fact textbooks have taken is approach, and if the mathematics accurately model the real word, optimum values may be achieved. Both linear and non linear problem formulations are possible, and network layer attributes of end–to–end connectivity, routing, and congestion have been formulated using this technique. However, due to the fact that analytical relationships are a critical component of this method, it seems likely that only a steady state type of design could be created using this approach.

Another issue with the Linear Programming approach is the question of the objective function. In most ad hoc networks, it is desire to optimize multiple networking objectives, potentially with its own mathematical equation. For example is it typically desired to optimize overall transmission energy as well as network throughput in an ad hoc network design. Thus multiple objective functions are required. The usual approach is to try to combine these multiple objective functions into a single equation, and there a number of standard ways of doing this. However, what usually happens is that one objective is optimized at the expense of another and a trade off then becomes possible.

The general LP problem formulation is:

Minimize f(**x**)

Where:

f(**x**) is the linear function in x to be minimized
x is a vector of decision variables (to be determined via the optimization)
A***x**= C is the matrix equality constraint equation
H***x** <= D is the matrix inequality constraint equation

Since the LP formulation, does not include uncertainty, the network design problem may be formulated as Stochastic Optimization problem. In Stochastic Optimization (R. Grote et. al., 2005), we specifically include the uncertainty in our design variables. The general Stochastic Optimization problem is formulated similar to the LP above, with the addition that the matrices, A, C, H, and D are now defined for a given scenario, and the LP result is taken over all possible scenarios.

5. AN APPROACH TO AD HOC NETWORK DESIGN

CERDEC–STCD is currently working on a program to develop a set of tools that can be used in the design of ad hoc networks. The tools, or more precise a tool set includes a number of integrated software packages that address the three major design levels of ad hoc networks are described in section 3 above. The toolset may include a number of optimization engines, for both linear and stochastic programming as described above. In addition, the toolset also may have links to the traditional discrete time event driven simulation package such as OPNET. A high level diagram of the toolset is provided at Figure 3.

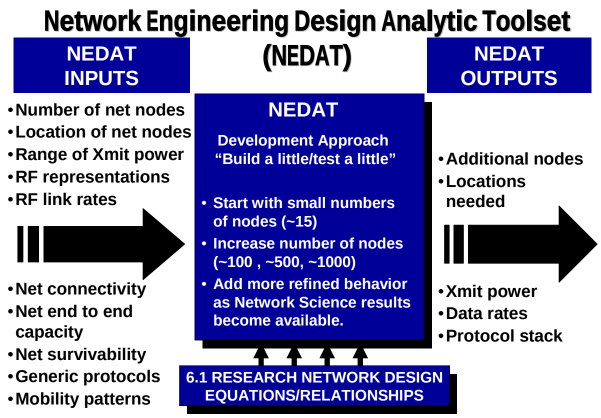

Figure 3. Conceptual view of Ad Hoc Network Design Toolset.

The basic operation of the toolset first takes inputs in form of network performance goals of connectivity, capacity, and survivability. Also as input are a range of design parameters such as maximum transmission power, nominal data rate, and a set of channel models with ranges for the characteristic parameters. The toolset then produces an initial and potentially mathematical optimal design. This design is then simulated with a more detailed event driven simulation environment, typically in OPNET, to determine if the design goals are meet. If the design goals are not meet, then the inputs are adjusted and a new design is produced. This cycle is repeated until all the network performance goals are achieved. This iterative design process is shown at Figure 4.

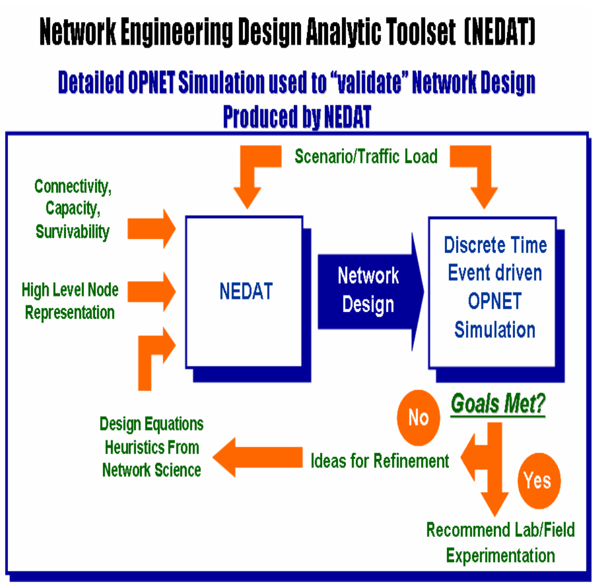

Figure 4. The Iterative Network Design Process.

6. NETWORK DESIGN RESEARCH ISSUES

One of the major issues in ad hoc network design is how to deals with uncertainty in the design process. Uncertainty manifests itself throughout the design process, but most specifically in the following areas:

6.1 Uncertainty in traffic loadings

It is well known that the particular design solution is highly dependent on the traffic loading that is applied to the network. The uncertainty is not only in the average applied load, but also in the peak load as well as the load distribution. In addition, the traffic is also highly time dependent as the battle or military action unfolds. While much work has on into a definition of the traffic loadings, it should be recognized that those data are best only engineering best guesses. Additionally, the traffic maybe voice, packet data, voice, imagery, or Situational Awareness (SA) type traffic. Both the traffic mix as well as the load for each traffic type is usually only estimated. Typically, what is usually done is to design for the "busy hour" or peak traffic load, under the assumption that that it is the worst case, and that if the network meets its performance goals at that load, it will most certainly meet them under lesser loadings. This may lead to an over designed network, it that the many network resources may be under utilized most of the time.

6.2 Uncertainty in node mobility

It should not be assumed that the individual nodes or group of nodes move through the network without some variation in their paths. This variation can be a result of the battle action, or battle damage. If a network is design without regard to the individual or group of nodes variation in position, then it is highly likely that an inefficient network design will result. (Byung–Jae Kwak, 2003).

6.3 More accurate and precise analytic models for ad hoc network end–to–end performance

One of the major problems areas in the development of a completely analytic design approach for ad hoc networks is the limited availability of analytic performance results. Most of the results available in the literature make numerous assumptions regarding the traffic arrival patterns (usually Poisson) and packet length distributions (usually exponential). In addition, for the multi hop case, were a packet is relayed multiple times from source to destination, the famous "Kleinrock Independence Assumption" is usually used to get analytic results. While these assumptions do provide an approximation to the network performance, measurements on real networks have consistently shown that they under estimate the average network end–to–end delay, and provide other optimistic results as well. Hence more realistic end–to–end mathematically models for multi-hop delay, throughput/goodput, packet loss probability, and survivability are key research areas that need to be addressed.

6.4 Accurate and Precise models for Broad Network Topology for ad hoc networks

As previously mentioned, directed graphs are usually used to present RF connectivity of a mobile ad hoc network. In this model, the graph vertices represent network nodes or switching points, and the arcs (which connect two nodes or vertices) represent the communication links. There are several problems with this representation, in that a single transmitted packet may be simultaneously (within the propagation delay) received by all nodes within the transmitters one hop radius. This can not be represented in the directed graph model. In addition, the effect of packet collisions and other types of interference also can not be represented as well. The main difficulty is that the arcs connect only two nodes (one source and one receiver), but actual reality is that a single source node may affect multiple receiving nodes (nearly) simultaneously. Hence, new and more accurate mathematical descriptions of the multi-hop broadcast radio environment are also needed.

6.5 More Accurate models for Node Mobility (Group and Individual)

Clearly mobility plays a major part in the design of mobile ad hoc networks. The basic problem is that node mobility is typically represented either as a fixed path through the network, or probabilistically in some fashion. In the probabilistic formulation, a number of alternatives are possible, including random motion (both in position and velocity), random wait pointing, where the node stops, and pauses and then randomly assumes a new direction and speed. However, none of these approaches accurately represent the military mobility on an operational sense. Additionally node or group of node location uncertainty must be addressed as indicated above.

It is also noted in most scenarios nodes move a group in a convoy like fashion. Hence the motion of a group of nodes is highly correlated and dependent on the battle activities as well.

6.6 Network models and Network designs that are scalable.

Another and important problem to be addressed is network scalability in the in the mathematical models used in network design as well as the resultant network design itself. Network scalability implies that as the network size (in terms of number of nodes) increases to potentially thousands of nodes, that both the network models as well as network design solutions still retain their desired functionality and performance. This problem has been and continues to be a major challenge for both the research and engineering communities.

7. CONCLUSIONS/RELEVANCE TO THE WARFIGHTER

This paper has summarized some of the basic issues in network design, provided a first order solution to them and identified some areas for future research. While today most ad hoc networks are design without a disciplined and analytic approach, we feel that the technology can be developed to provide a design toolset for the ad hoc network environment similar to that used in the digital cellular and fiber optic network environments.

The advantage to the Warfighter is that the future and emerging ad hoc networks will provide better and more reliable network performance that those that were designed without the benefit of a toolset. In addition, engineering personnel can use the toolset to provide rapid and reliable cost benefit trade–off analyses leading to more cost effective and optimum solutions than those previously obtained.

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